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13. ABSTRACT (maximum 200 words)

Rare earth doped fluoride single crystal planar and channel waveguides have been prepared using molecular beam epitaxy (MBE). They offer the potential for an attractive new class of visible and near infrared laser oscillators and amplifiers, particularly in the configuration described in this work, where the fluoride devices are integrated with a substrate (GaAs) that can carry the required semiconductor diode pump laser. The fluoride layers have been characterized structurally and optically to establish the growth conditions and waveguide dimensions for minimum optical propagation loss. We have demonstrated loss as low as 3.7 db/cm, a value still greater than our target of less than 0.1 to 0.5 db/cm. Infrared driven upconversion leads to visible emission from Erbium and Neodymiumn and has been shown for a number of hosts, the most promising of which is LaF_3. The spectroscopy of the active rare earth ions and the dynamics of energy exchange in doubly doped systems has been explored for several important combinations using both rate equation models and a Monte Carlo computation. Current work is directed at detailed structural investigation for a simpler two component structure (active/cladding) to identify the origin of the losses observed (surface scattering or bulk loss at grain boundaries).

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Introduction

The objective of this program is the development of techniques for fabricating rare earth doped planar and channel waveguides in fluoride crystalline hosts and of operating these devices as oscillators and amplifiers in the spectral region 0.4 to 1.5 microns. The use of infrared semiconductor diode laser sources as pumps for these new types of lasers offers novel compact and efficient device potential for both upconversion visible lasers and for infrared downconversion operation.

The use of molecular beam epitaxial (MBE) growth of rare earth doped fluoride materials for waveguide laser preparation is being carried out for the first time on this program. It has required the implementation of high vacuum apparatus of a kind used typically for semiconductor device materials and the research effort has both a materials growth and characterization task and a task concerned with optical measurements of the waveguides and of operating these devices as lasers and amplifiers.

The effort for the last year has involved contributions from a number of laboratories including the Hughes Research Laboratories, the Electrical Engineering Department at UCLA, the Materials Research Laboratory at UCSB, the Institute of Applied Physics, University of Bern Switzerland, the Institute of Inorganic Chemistry, University of Bern Switzerland, the Institute of Laser Physics, University of Hamburg Germany, CREOL, University of Central Florida, the XEROX Palo Alto Research Center, the IBM Research Division, Zurich Research Laboratory, the USC Center for Laser Studies and the Instituto Tecnológico de León, México.

During this period, three PhD theses were completed, extracted parts of which are included in the several technical publications or completed manuscripts which comprise the bulk of the present report. The development of kinetic models describing energy transfer in doubly doped hosts is discussed in two papers. The objective is the realization of optimum doping levels in such systems for laser oscillator and amplifier applications. A particular example is the Yb:Pr system of interest for visible upconversion laser purposes. This was examined using a rate equation model and will be of importance for MBE dual doped fluoride materials in planar and channel waveguide configurations that can replace ZBLAN glass fiber lasers. By this means it is expected to avoid the development over time of optical propagation losses found to occur in ZBLAN due to the generation of color centers as the charge state of Zr changes from 3+ to 4+. A different computational technique to examine energy exchange in hosts doubly doped with rare earths employs a Monte Carlo description of multipolar interactions that lead to an extremely rapid transient energy exchange.

The Yb:Tm system has been important for room temperature infrared pumped bulk visible laser devices. It has very great potential for MBE waveguide devices based on Yb:Tm codoped fluorides, in particular LaF_3 host material as discussed in one of the papers in this report. Initial attempts at Kodak with glassy layers of $BaYbYF_8$:Tm prepared by thermal and e-beam evaporation have produced less than adequate material. Because of less than ideal structural characteristics, those layers that demonstrated upconversion were found to have very high optical losses and spectral linewidths significantly broader than for the crystal systems we are using for the MBE layers. Our present techniques offers the potential for achieving better low loss single crystal channel guides and should be capable of operating with very low pump power requirements since the channel guide confinement maintains high pump power density over the entire length of the guide. We expect the single crystal structure we have confirmed in our MBE layers to be a greatly superior laser candidate.

An extensive spectroscopic study of Bridgman grown $BaYbYF_8$:Tm crystals was performed in collaboration with UC Santa Barbara.* Detailed Stark energy level structure for the Tm^{3+} ion was determined and the importance demonstrated of the relationship of the laser polarization direction to the crystal axes.

Discussion of Program Status

A critical parameter in the development of MBE grown structures for the laser and amplifier applications is the optical propagation characteristics of the planar and channel waveguides. Channel waveguide lasers have been reported using both ion implantation to define the active region and an ion beam etching process followed by overgrowth to prepare a buried channel. Lasers have been operated with waveguide losses as high as 2.0 db/cm. We have achieved propagation losses for MBE grown layers as low as 3.7 db/cm for LaF_3/SrF_2/GaAs structures. The analysis of mode confinement as a function of cladding layer thickness suggests that tailing into the GaAs substrate may be responsible for some of this loss. With the objective of reducing losses in these guides, we have started the fabrication of LaF_3 guides on SrF_2(111) substrate discs alone without the use of a GaAs substrate. The desire is to achieve a waveguide structure that maintains excellent crystallinity resulting from a good lattice match of the fluorides and to avoid the very large thermal expansion differential (~8:1) with GaAs This differential limits the layer thickness than can be prepared before it fails on cooling as well as establishes a limit to the range of successful growth temperatures.

To prepare the SrF_2(111) substrates for MBE growth, we use an HCl chemical etch and examine the surface under a Nomarski microscope to evaluate surface smoothness. The choice of (111) orientation follows our determination that this orientation is required for the GaAs substrates and that it provides an initial growth surface appropriate for the almost hexagonal LaF_3 crystal structure. In addition, we find that starting with SrF_2(100) discs results in pyramidal surface structures upon chemical etching that are associated with a crystal-plane-dependent chemical etch rate. Currently several 1 inch diameter (111) disks have been prepared and are ready for growing the LaF_3 planar waveguide layers.

A substrate heater failure is currently being repaired following delivery of a replacement carbon serpentine planar unit. The shutdown of the entire growth system to accomplish this installation has necessitated a major disassembly of the vacuum system and will require an extended bake out before we can resume growing of the LaF_3 layers. It is expected that we will grow on the new discs in a matter of days.

The measurement of the active layer thickness, its refractive index and propagation loss for the planar guides grown on these new SrF_2 discs will be made before fabricating waveguide channels. This requires the determination of the "m-lines" for the structure using a goniometer controlled prism coupler. Result of such measurements on the previously prepared LaF_3/SrF_2/GaAs structures are discussed in a paper we have recently published in the Journal of Lightwave Technology.

As yet unpublished work in France has explored Yb:Er codoping of CaF_2 MBE layers and it is apparent that critical materials issues remain to be examined. This group has found that growth conditions are important controlling factors in how the Yb^{3+} ion is incorporated as a sensitizer and consequently for the energy transfer efficiency. Since the French spectroscopic observations were made at low sample temperatures, (25K) it was possible to observe more complex centers, inequivalent sites and clusters that

occur, particularly at high dopant concentrations. The use of LaF_3, which admits of substitutional replacement of Lanthanum by the rare earth ions, and does not require a complicated charge compensation process to take place, is expected to avoid these line broadening scenarios.

Theses completed at the Hughes Malibu Laboratories or in collaboration with HRL

1. Jonathan Joseph Owen, "Rare-Earth Doped Barium Yttrium Fluoride: Crystal Growth and Applications in Upconversion Lasers". Doctor of Philosophy in Materials, University of California, Santa Barbara, 1995.

2. Deborah Janice Vickers, "Kinetics and Energy Transfer Studies of Praseodymium and Ytterbium in $YbLiF_4$ for Sensitized Upconversion Lasers". Doctor of Philosophy in Electrical Engineering, University of California, Los Angeles. 1996.

3. Markus Pollnau, "Population Mechanisms in Erbium-Doped Solid State Lasers". Doctor of Philosophy in Physics, University of Hamburg, Hamburg Germany. 1996.